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Peculiarities in equilibrium tunneling between disordered two-dimensional electron systems: from Fermi edge singularity to linear gap in high magnetic field

Yu. V. Dubrovskii[1], R. Hill[2], V. A. Volkov[3], V. G. Popov[1], E. E. Vdovin[1], D. Yu. Ivanov[1], A. Kotel'nikov, L. Eaves[2], P. C. Main[2], D. K. Maude[4], J.-C. Portal[4,6,7], M. Henini[2], G. Hill[5] and J. C. Maan[8]
[1] Institute of Microelectronics Technology RAS, 142432 Chernogolovka, Russia
[2] The School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom
[3] Institute of Electronics and Radioengineering RAS, Moscow, Russia
[4] Grenoble High Magnetic Field Laboratory, MPI-CNRS, BP166 38042 Grenoble Cedex 9, France
[5] Dept of Electr. and Electron. Eng., University of Sheffield, Sheffield S3 3JD, UK
[6] Institut Universitaire de France
[7] INSA, F31077 Toulouse Cedex 4, France
[8] High Field Magnet Laboratory, Research Institute for Materials, University of Nijmegen, 6525 ED Nijmegen, The Netherlands

Abstract. We have investigated equilibrium tunnelling between disordered two-dimensional electron systems at temperatures below 0.3 K and in a wide range of magnetic field normal to the electron layers. Observed transformation of a narrow conductance peak of about 1 mV width at zero bias into the narrow dip with magnetic field is discussed in the frame of many-electron interaction effects in tunnel phenomena.

It was discovered recently that a high magnetic field normal to the layers suppresses equilibrium tunnelling between two-dimensional electron systems [1–3] and between 2D and 3D electron systems [4]. These studies were performed on samples with low [2–4] or very low disorder in the 2D electron gas [1]. There is general agreement that the observed suppression is related to in-plane Coulomb correlations between 2D electrons in a high magnetic field. Equilibrium tunnelling between strongly disordered electron systems has been recently studied only for the case of 3D electron systems [5], where a gap in the tunnelling density of states in zero magnetic field was reported. Earlier we reported that high magnetic field $B > 8$ T parallel to the current suppresses tunnelling between disordered two-dimensional electron systems near zero bias [6]. These studies were performed at temperatures above 2.4 K. It was found that the main features related with tunnelling gap appeared in a high magnetic field in temperature range used was similar to those found in samples with low disorder [2, 3].

In this work we present studies of tunnelling between two strongly disordered two-dimensional electron systems (2DES) at temperature lower then before ($T \leq 0.3$ K) in a magnetic field parallel to the current, that is normal to the electron layers. We have found extra equilibrium tunnel current without magnetic field which was manifested as very narrow conductance peak at zero bias. The gap in tunnel spectra appears at zero bias in magnetic field about 4 T with disappearance of the extra current features at the same time. Analysis shows that the gap has linear form, and the slope of the gap oscillate with magnetic field. It is possible also to extract from the data the gap width and depth dependences on

magnetic field. We argue that wide differential conductance maximums on both sides of the gap in the tunnel spectra measured in a high magnetic field are due to the energy relaxation of tunnelling electrons by emission of some kind quasi-particles.

To form the 2DES we used Si donors sheets (δ-doped layers) with the donor concentration corresponding to insulator behaviour in electron transport [7, 8], i.e. slightly below the metal–insulator transition at zero magnetic field. In our experiments, electron transport along the layers does not contribute to the measured current which flows perpendicular to the plane of the barrier. This allows us to measure the zero-bias conductance which is proportional to the convolution of the tunnelling density of states.

The MBE-grown sample was a single barrier GaAs/$Al_{0.4}Ga_{0.6}As$/GaAs heterostructure with a 12 nm thick barrier. The barrier was separated from the highly-doped, bulk contact regions by 50 nm thick, undoped GaAs spacer layers. Si donors sheets with concentration of $3 \cdot 10^{11}$ cm^{-2} were located 5 nm from each side of the barrier. The tunnelling transparency of the main barrier was much lower than that of the spacer regions, so that most of the applied voltage is dropped across the barrier.

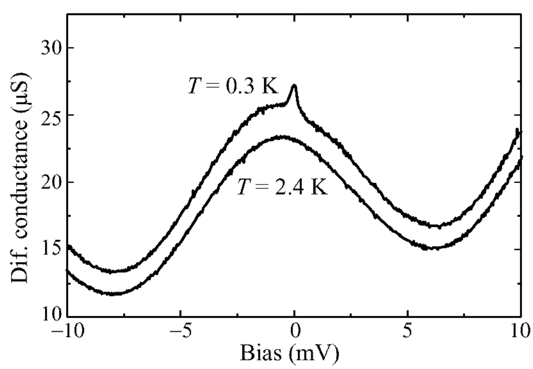

Fig. 1. Tunnelling differential conductance at 0.3 K and 2.4 K as a function of external voltage in zero magnetic field. Curves arbitrary shifted in vertical direction for clarity.

Figure 1 shows the differential tunnel conductance G, at 0.3 K and 2.6 K, measured using standard lock-in techniques, versus external voltage V_b in zero magnetic field. At 2.6 K the differential conductance has a wide peak around zero bias. We argue that peak reflects resonant tunnelling between the ground states of the 2DESs. The maximum of the peak is slightly shifted (1 mV) from zero bias since as grown concentrations in the layers is slightly different. At 0.3 K additional narrow conductance peak with maximum exactly at zero bias is perfectly resolved.

Figure 2(a) shows that this narrow conductance peak transforms into the dip with magnetic field. It happens in B between 3.5 and 4 T. Further variation of the tunnel spectra with magnetic field in B ranged from 7 T to 15 T is shown in Fig. 2(b).

In this work, we focuse on the equilibrium tunnelling processes around zero bias and start with the analysis of the dip appeared in magnetic field. The tunnelling differential conductance at low voltage reflects the joint density of states at the Fermi levels in the 2D electron layers. We found that differential conductance in a dip around zero bias has parabolic dependence on bias voltage at all magnetic fields, which is the main difference from the systems with low disorder where exponential increase of the current around the gap ("hard" gap) created by magnetic field was found [2, 3]. The parabolic form of differential conductance corresponds to the linear gap in the density of states near Fermi level in each

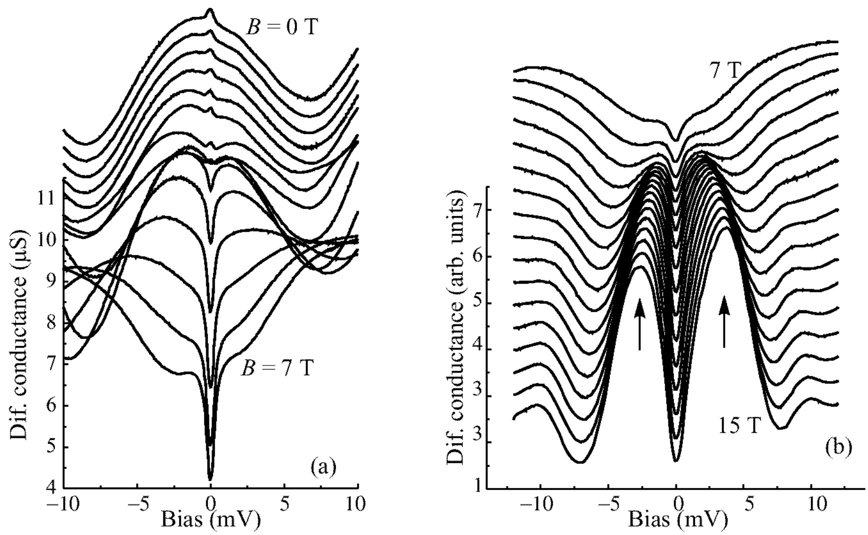

Fig. 2. (a) Tunnelling differential conductance at 0.3 K as a function of external voltage in different magnetic fields from 0 T up to 7 T with 0.5 T magnetic field step between the curves. Curves arbitrary shifted in vertical direction for clarity. (b) Tunnelling differential conductance at 0.3 K as a function of external voltage in different magnetic fields from 7 T up to 15 T with 0.5 T magnetic field step between the curves. Arrows indicate differential conductance peaks discussed in the text. Curves arbitrary shifted in vertical direction for clarity.

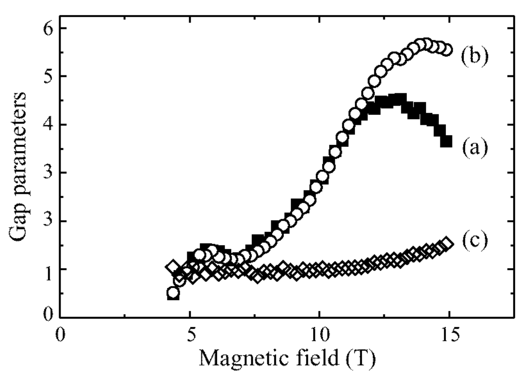

Fig. 3. (a) The slope of the linear gap in arbitrary units, (b) the depth of the linear gap in arbitrary units, (c) the width of the gap in mV, all versus magnetic field normal to the 2DES.

2DES. The existence of the "soft" linear gap in the density of states near Fermi level due to the Coulomb interaction of localised electrons was found theoretically many years ago by Efros and Shklovskii [9]. Since the localisation is increased with magnetic field it is not surprise that the dip due to the gap in the density of states appears in the tunnel spectra only in a magnetic field when most of the states along the 2DEG becomes localised. But behaviour of the gap with magnetic field is unusual and until now has not been described in the literature. The dependence of the slope of the linear gap, that is the coefficient at quadratic term describing the experimental parabolic dependence, versus magnetic field is shown in Fig. 3. The slope oscillates with B. In the same Fig. 3 the width and depth

of the gap as function of magnetic field are shown also. The width was determined in the preposition that the gap are terminated at point where dependence of the differential conductance on bias voltage becomes sublinear, and was extracted from the position of extremums on the conductance derivative plot. The depth value was obtained from the values of slope and width of the gap.

The wide peaks in the differential conductance appeared in a high magnetic fields out of the gap, shifted linear with magnetic field, and shown in Fig. 2(b) by arrows are similar to those which was found before in tunnelling between 2DES with different level of disorder [1–3, 6]. For samples with very low disorder it was proposed that wide peaks appeared out of tunnelling "hard" gap was due to the relaxation of tunnelling electron into the ground state with emission of some kind of quasiparticles [10, 11], e.g. plasmon vortexes [10], or some specific oscillations in the electron system [11].

Coming back to the narrow conductance peak at zero bias without magnetic field we argue that it is related with the tunnelling from the puddles with strongly localised states in the emitter into the puddles of 2D extended states in the collector. That is well known Fermi edge singularity and was observed before in tunnelling between 2D and zero-dimensional impurity states [12]. The donor concentration fluctuates along the 2DES in our structure. So one could find the regions with low concentration of strongly localised electrons and regions of high enough concentration with extended 2D electrons states. Since the fluctuation in the electron systems on different sides of the barrier are independent, there should exist regions where electrons tunnel from localised to extended states. Magnetic field suppresses extended states and Fermi edge singularity is disappeared from tunnel spectra.

In conclusion, we have investigated equilibrium tunnelling between disordered two-dimensional electron systems at temperatures below 0.3 K and in a wide range of magnetic field normal to electron layers. The Coulomb interaction between electrons in the layers leads to the different anomalies found in the tunnel spectra: Fermi edge singularity in zero magnetic field and linear gap in the density of states developed in magnetic field. The slope of the linear gap oscillates with magnetic field. At the moment we do not know any theoretical model describing gap behaviour with magnetic field.

Acknowledgements

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References

[1] J. P. Eisenstein *et al.*, *Phys. Rev. Lett.* **69**, 3804 (1992).
[2] N. Turner *et al.*, *Phys. Rev.* **B54**, 10614 (1996).
[3] Yu. V. Dubrovskii *et al.*, *JETP Letters* **69**, 255 (1999).
[4] R. C. Ashoori *et al.*, *Phys. Rev.* **B48**, 4616 (1993).
[5] M. Lee *et al.*, *Phys. Rev.* **B60**, 1582 (1999).
[6] Yu. N. Khanin *et al.*, *Physica E* **6**, 602 (2000).
[7] Qiu-Yi Ye *et al.*, *Semicond. Sci. Technol.* **4**, 500 (1989).
[8] R. J. F.Hughes *et al.*, *J. Phys.: Condens. Matter* **6**, 4763 (1994).
[9] A. L. Efros and B. I. Shklovskii, *J. Phys C: Solid State Phys* **8**, 49 (1975).
[10] I. L. Aleiner *et al.*, *Phys. Rev. Lett.* **74**, 3435 (1995).
[11] P. Johansen and J. M. Kinaret, *Phys. Rev. Lett.* **71**, 1435 (1993).
[12] A. K. Geim *et al.*, *Phys. Rev. Lett.* **72**, 2061 (1994).